Simulation of High-Voltage Discharge Channel in Waterat Electro-Hydraulic Forming Using LS-DYNA®

V. Mamutov
St. Petersburg State Polytechnical University, Russia
S. Golovashchenko
Ford Motor Company, Scientific Research Laboratory, USA
A. Mamutov
Oakland University, USA

Abstract

The method of simulating of expansion of plasma channel during high-voltage discharge in water at electro-hydraulic forming (EHF) is developed using finite-element software package LS-DYNA 971. The energy input into the plasma channel from the discharge circuit is taken into account. The energy deposit law is calculated from the experimentally obtained pulse current and voltage in the discharge circuit measured between the electrodes. The model of discharge channel is based on assumption of adiabatic channel expansion when the energy introduced into the channel from the external electrical circuit is only spent on increasing the internal energy of plasma and on the work of plasma expansion. Water is simulated as an ideally compressible liquid with bulk modulus of K = 2.35 GPa. The cavitation threshold for the liquid is defined as 0.1 MPa. The interaction between the channel and the water is simulated using Arbitrary Lagrange Eulerian (ALE) technique. The deformable blank is simulated using shell elements. The results of simulation of two variants of the discharge chamber are presented: for the long cylindrical chamber with long axisymmetrical discharge channel and for the compact chamber of arbitrary shape with short discharge distance. The developed numerical method is verified by comparing the results of simulation with the results from the test simulation, which is a one-dimensional axisymmetric finite-difference based problem with the same parameters. It is also verified by comparing the results of simulation and the experimentally measured pulse pressure in the discharge chamber with a known function of energy input.

Introduction

The electro-hydraulic effect is an explosion-like phenomenon which happens when a high-voltage electrical discharge is performed between two electrodes submerged in a liquid, typically water. Shock waves and high-velocity stream that accompany the expansion of discharge channel can be used in variety of applications. Most widely, the electro-hydraulic effect is used in sheet-metal forming applications, in the process called electro-hydraulic forming (EHF) [1-3]. The advantages of EHF before conventional sheet-metal forming applications, among others, include reducing the cost of stamping tools due to the lack of second rigid tool, improving the formability and reducing springback due to the high-velocity nature of deformation process and blank-die contact. To define parameters of technological process, to design tools and equipment

for EHF, it is crucial to be able to calculate the parameters of pulse pressure in the liquid during a discharge.
The EHF process is characterized by relatively high amplitude (up to 2GPa) and short rise time of pulse pressure (0.1…10μs) near the discharge channel during initial channel expansion. From the other hand, the overall duration of the process can reach few ms with pressure dropping significantly and water behavior resembling an incompressible water stream. A simulation software must be able to simulate both periods of the process and also take into account highly nonlinear behavior of deformable blank and complex contact picture of liquid interacting with the blank and the blank interacting with the die. One of the most appropriate systems is the finite-element code LS-DYNA.
In the paper, the model of discharge channel is developed and applied for simulating the EHF process using LS-DYNA 971 [4].

Model of discharge channel in liquid

The energy balance in the discharge channel is defined by the following equation [5]

$$E_{pl} + A + E_{ls} = \int_0^t N(t)dt, \qquad (1)$$

where E_{pl} – internal energy in the plasma from which the discharge channel consist, A – the mechanical work performed by expanding plasma cavity, E_{ls} – summary loss of energy trough different ways (thermal conduction, radiation, etc.), $N(t)$ – energy deposited into the channel from the electrical current.
The internal energy of plasma in the channel is defined by the following equation of state (EOS) for the ideal gas:

$E_{pl} = p_{ch}V_{ch}/(\gamma - 1),$

where p_{ch} – pressure in the channel, V_{ch} – channel's volume, γ – adiabatic index for the plasma obtained from the tap water and material of initiating wire. Adiabatic index is dependent on pressure, temperature, and chemical composition of plasma. The typical value of γ in EHF conditions, according to most sources, is varying in the narrow boundaries $\gamma \in$ [1.24…1.26], even when using initiating conductor.
The work performed by expanding the channel is defined as

$$A = \int_{V_{ch0}}^{V_{ch}} p_{ch}\, dV_{ch},$$

where V_{ch0} – initial volume of the channel.
The energy losses E_{ls} are defined mostly by electromagnetic radiation of plasma and also by energy of evaporation of liquid surrounding the channel. In the typical conditions of EHF process, the radiation energy does not exceed 10% of total deposited energy, and evaporation process at the channel boundary is significantly slower than mechanical expansion of the channel. Therefore, the boundary is assumed adiabatic [5], and the value E_{ls} in energy balance equation (1) is neglected.

Simulation of the test problem. Input data

The test problem is an electrical discharge in the axisymmetric cylindrical chamber. Such a simple shape of the chamber allows easy comparison of results of numerical simulation and experimental data. The scheme of the test equipment is shown in figure 1.

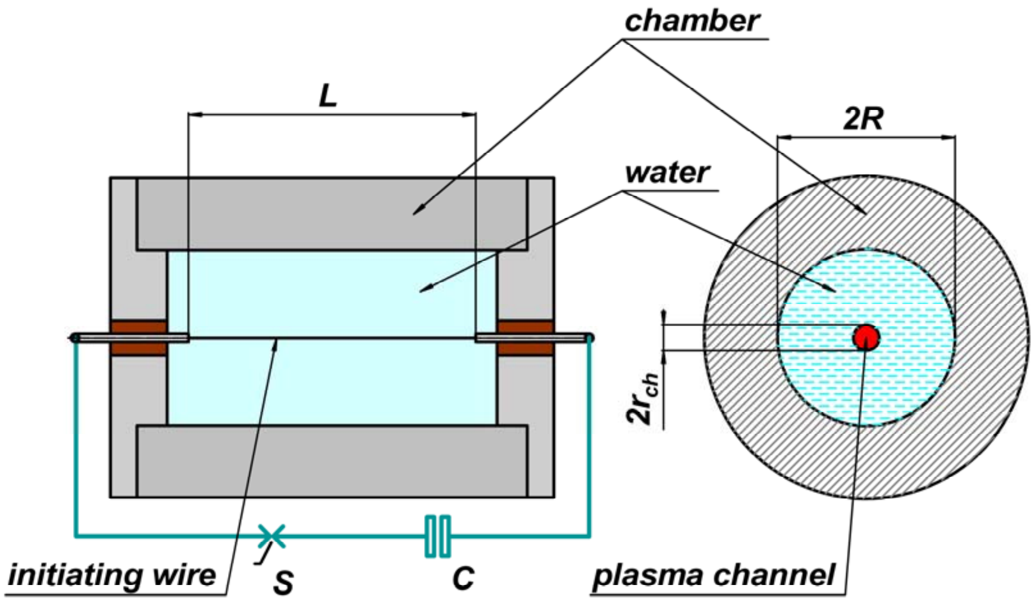


Figure 1. The scheme of the test equipment

The cylindrical chamber of radius *R* and length *L* has electrodes placed on the two opposite walls. A nichrome wire of 0.3 mm diameter is used as initiator. The tap water is used as a working liquid. After discharge of the capacitor battery *C* on electrodes, the cylindrical axisymmetric shock wave is propagating to the chamber walls where the resulting pulse pressure is registered using a piezoelectric pressure sensor. The obtained value of the pressure and also the discharge voltage and the current are recorded using impulse oscilloscope.
The dimensions of the chamber are: L = 160 mm and R = 50 mm. With such dimensions, the boundary effects from the side walls that disturb radial symmetry of the cylindrical pressure wave will not reach the center of the chamber cylindrical wall before the maximum pressure value will be captured by the sensor. The pulse generator parameters are: capacity of the battery C = 50 μF, charging voltage U = 10 kV. The function of energy deposition in the discharge channel is defined as a multiplication of experimentally measured current and voltage

$N(t) = u(t) \cdot i(t).$

The resulting curve can by approximated for convenience by the following law

$N(t) = 1.79 \cdot N_0 \cdot \exp(1.32\ t/\tau) \cdot \sin(\pi t/\tau),$

where τ = 52 μs – half-period of discharge current oscillation, N_0 = 72 MW – amplitude of the electrical power.

Building model for LS-DYNA 971

MATERIAL OF PLASMA CHANNEL

In LS-DYNA 971 the equation of the energy balance of ideal gas with an energy input can be defined using the card EOS_LINEAR_POLYNOMIAL_WITH_ENERGY_LEAK which defines the equation of state as polinom

$$p_{ch} = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)\, N(t) / V_{ch0}, \qquad \mu = 1/V - 1,$$

where V – relative volume, defined as density of the material at current moment divided by its initial density. The constants $C_0 - C_6$ are chosen to adjust this general equation into the form of equation (1)

$C_0 = C_1 = C_2 = C_3 = C_6 = 0,$
$C_4 = C_5 = \gamma - 1.$

The EOS card is used together with MAT_NULL card, to define the material of discharge channel. This card defines the initial density of the plasma channel ρ_{p0}. The value of initial density is difficult to determine both experimentally or theoretically; therefore, it is defined based on numerical stability consideration and convenience of meshing. In presented models, the initial density is defined as the initial density of water ρ_{p0} = 1000 kg/m^3, and initial radius of the channel in the cylindrical chamber is taken as 1.0 mm.

MATERIAL OF WATER

For the water, the model of MAT_ELASTIC_FLUID is used which defines pressure in the liquid as

$$p = -K \cdot ln(\rho_0/\rho), \qquad (2)$$

where ρ – liquid density, ρ_o = 1000 kg/m^3 – initial liquid density. The bulk modulus K is defined from approximation of Tait adiabat for water in the pressure range $p \in [0.1\ldots100]$ MPa, which gives approximate value of $K \cong 2.35$ GPa. The cavitation threshold is defined as 0.1 MPa.

MESHING

The chamber walls are assumed as perfectly rigid and were defined using boundary conditions to simplify the model. The plain-strain two-dimensional model is build using emulation of 2D model with one layer of hexa elements restrained with sliding boundary conditions.

THE RESULTS OF SIMULATION

Simulation results of plasma cavity expansion and pressure distribution in cylindrical chamber for two moments of time: $t \cong 12.0$ μs, $t \cong 87.9$ μs are shown in figure 2.

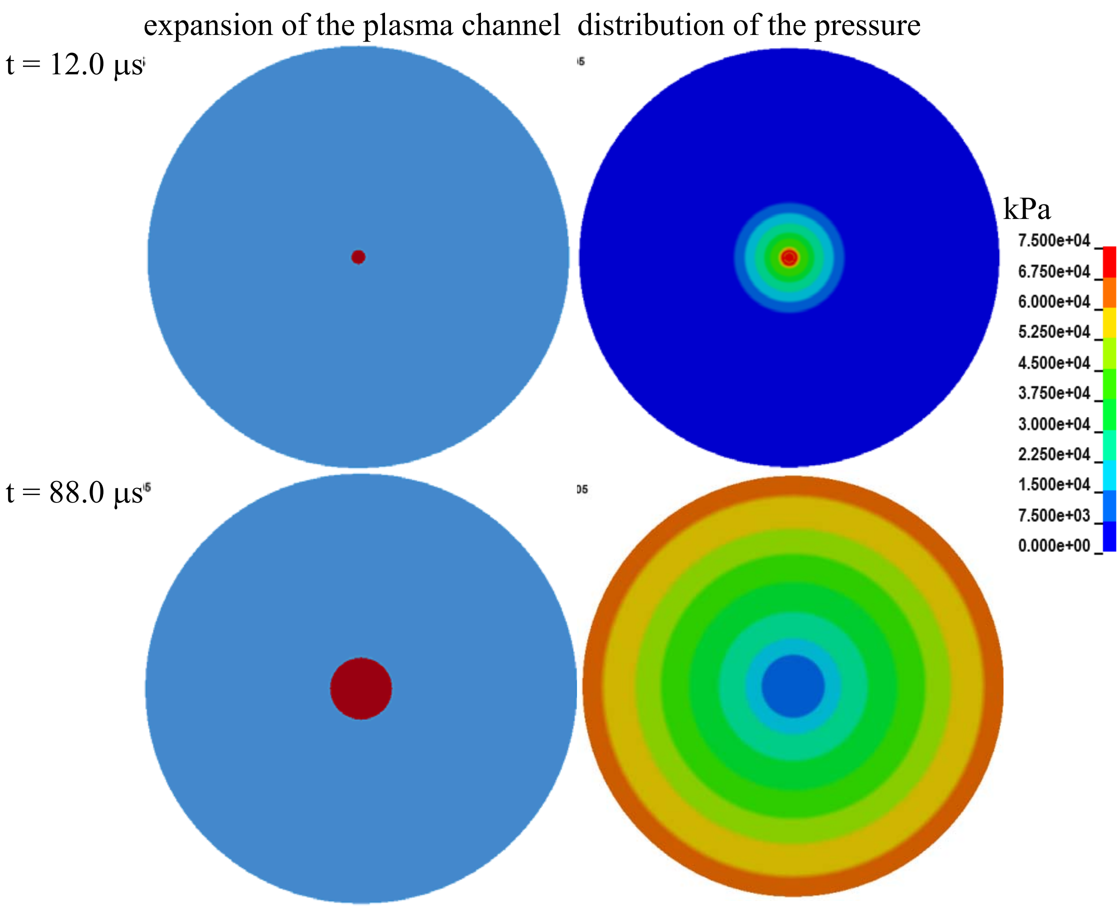


Figure 2. Simulation results for cylindrical chamber

VERIFICATION OF THE RESULTS

The results of the simulation are compared with the results of the in-house one-dimensional simulation performed using finite-difference (FD) approach. The equation of motion in Lagrangian form is as follows [6]:

$$\frac{\partial \upsilon}{\partial t} = -\frac{r(r_0,t)}{\rho_0 r_0}\frac{\partial p}{\partial t}, \quad \upsilon = \partial r / \partial t, \tag{3}$$

where r – Eulerian (initial) coordinate of material of fluid, r_0 – Lagrangian (current) coordinate, υ – radial velocity. The equation (3) is solved numerically with the same fluids' properties, initial and boundary conditions (1, 2) as defined for LS-DYNA problem.

Figure 3 shows comparison of the LS-DYNA results, the FD problem results, and the experimental results. The graph shows the pressure at the middle point of the cylindrical chamber wall. It can be emphasized that the results from all three sources are in good agreement with each other. Some difference between FE solution obtained form LS-DYNA and from the FD problem can be explained by different nature of numerical algorithms and by the different meshing density. As expected, the experimental pressure starts to diverge from calculated after boundary wave effects from the side walls reach the center of the chamber.

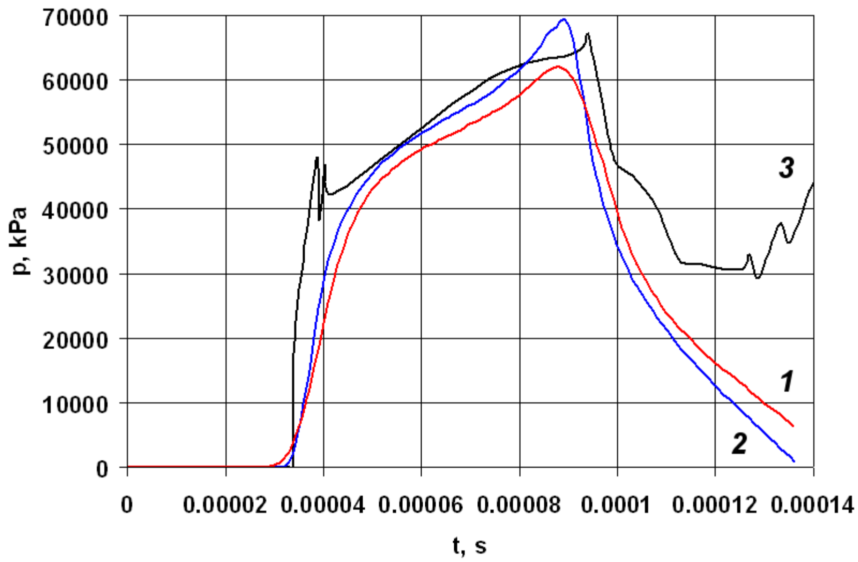


Figure 3. Pressure on the cylindrical wall of the chamber:
1 – LS-DYNA, 2 – numerical results from one-dimensional finite-difference problem, 3 – experimental results

Simulation of complex 3-dimensional problem

A typical EHF technology, as a variant of sheet stamping process, has complex geometry of tools and blank which poses additional challenges for simulation of such processes. Here, the simulation of EHF process with complex electrode system is presented. The design of the simulated process is shown in figure 4.

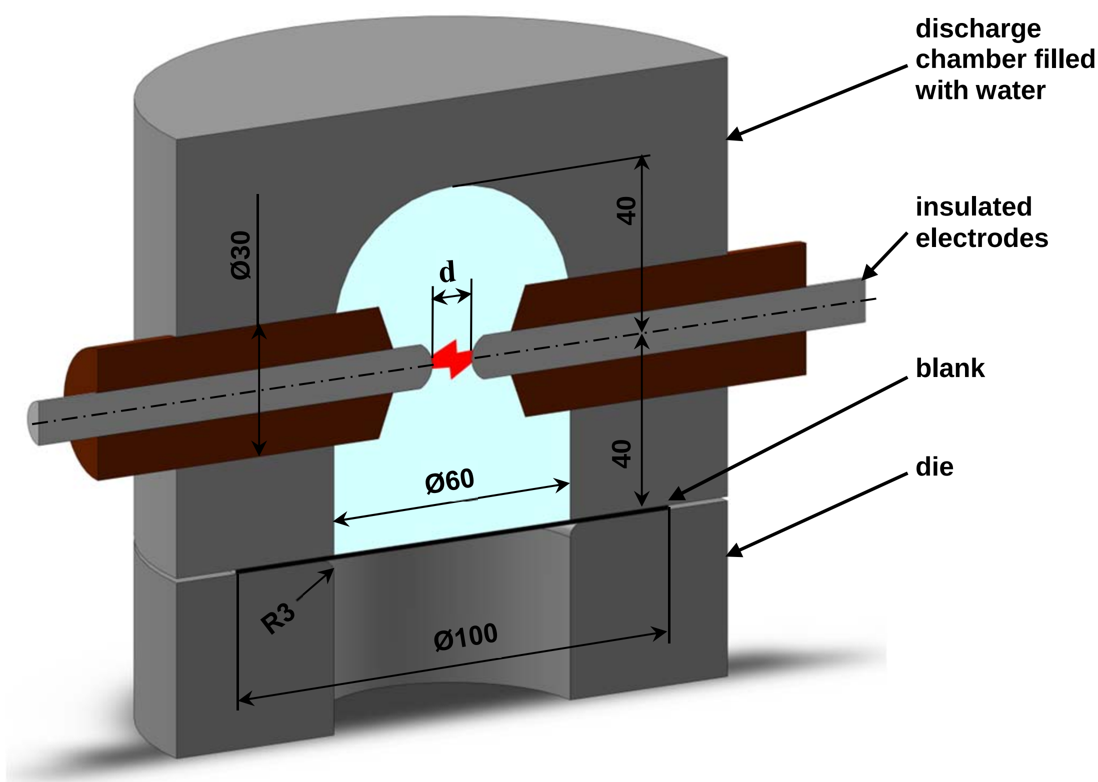


Figure 4. Tool for EHF process

CHOICE OF SUITABLE SOLVER AND MESHING TECHNIQUE

The first attempt to build a model for the real-life EHF process was done using Lagrangian approach to build a mesh for liquid and plasma. Although it is possible to use Lagrangian mesh in simulation of EHF, and the previously described test problem can be simulated using this approach, it is nearly impossible to use it for a complex geometry.
The first issue with Lagrangian mesh is necessity to adapt it to the features of chamber's interior, and, therefore, every problem requires its own unique meshing approach. That makes the meshing process sophisticated and time consuming.
The next and major issue is the mesh distortion during a simulation. The sources of excessive distortion are: the increase of the channel's volume order of magnitude three to four, deformation of the channel and liquid meshes, contact between liquid and structures and between plasma and liquid. The distortion of the channel mesh during expansion can be partially compensated using ALE Smoothing option, but it does not compensate all the distortion. The most excessive deformation of the mesh happens in contact between parts due to the lack of shear stiffness in fluids. The deformation of elements usually makes it impossible to continue the simulation at some moment because of a very small time step or a numerical instability.
In order to reduce mesh distortion, a simplification of the chamber and the electrodes shape can be used. For example, electrodes can be made with spherical tips, which make mesh simpler and sliding of the plasma and liquid mesh around electrodes easier. Nevertheless, even with simplifications, when using Lagrangian mesh, the simulation becomes unstable, typically at the moment when channel starts to collapse. The typical achievable simulation time, depending on complexity of a problem, is 300…1000 μs which is not enough for most practical cases.
There are also few contact issues when using Lagrangian mesh. It is almost impossible to define stable contact between plasma and liquid parts using algorithms available in LS-DYNA. The most reliable way is to avoid contact definition at all and to use shared nodes between parts. Another issue is a contact between fluids and structures, especially between plasma and structures which happens at the electrodes ends. The penalty based contact does not work well because the penalty factor is chosen internally based on such parameters of the material as density, stiffness, and element size, which all changes 2-3 order of magnitude within the plasma part. Therefore, it is impossible to define stable parameters for all contact points at all moments of simulation. Another option, constraint based contact, has limitations and also does not provide satisfactory results.
To avoid these problems the Multi-Material Arbitrary Lagrange-Eulerian (ALE) solver is used. When MM ALE approach is used, the mesh is not moving; instead, the physical materials (multi-material groups) are moving through the steady vacuum mesh allowing more than one material inside one geometrical element. The MM ALE approach makes meshing a routine task. It also eliminates the problem of mesh distortion. Contact between fluids and Lagrangian structures (chamber and blank) is defined using Fluid-Structure Interaction (FSI) capabilities. It works stable in wide range of variation of fluids' properties (density and pressure).
The deformable blank is meshed with shell elements. The MAT_POWER_LAW_PLASTICITY card is used to describe material of steel.

INPUT DATA FOR SIMULATION

The energy deposition law obtained experimentally is shown in figure 5. The simplified form of the curve is based on the method of elimination of electromagnetic noise in voltage divider used for measuring the voltage between the electrodes [7].

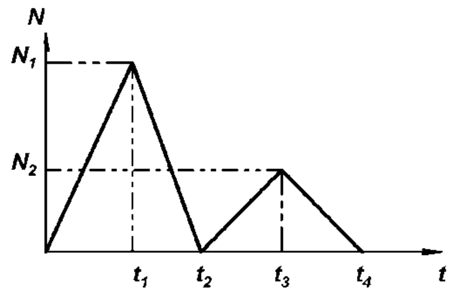
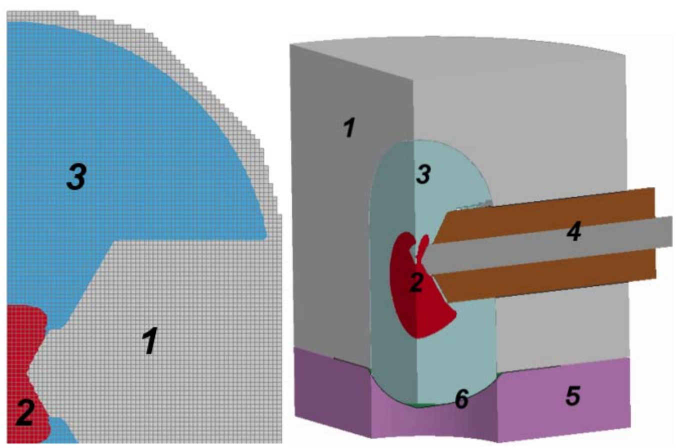


Figure 5. Energy deposition law: t_1 = 24 µs, t_2 = 49 µs, t_3 = 76 µs, t_4 = 102 µs, N_1 = 9.1 MW, N_2 = 4.9°MW

The blank's material is stainless steel which is equivalent to grade 321H steel; thickness 0.2 mm.

THE RESULTS OF SIMULATION AND EXPERIMENTAL VERIFICATION

The details of meshing strategy are shown in figure 6.a along with the shape of the channel at the moment 245 µs (figure 6.b).



a) *b*)

Figure 6. ALE mesh and deformation of the fluid parts and the blank at the moment 245 µs (*a*: 1 – vacuum mesh, 2 – plasma MM group, 3 – water MM group; *b*: 1 – discharge chamber, 2 – plasma bubble, 3 – water, 4 – electrode, 5 – die, 6 – deforming blank)

The distribution of pulse pressure is shown in figure 7.

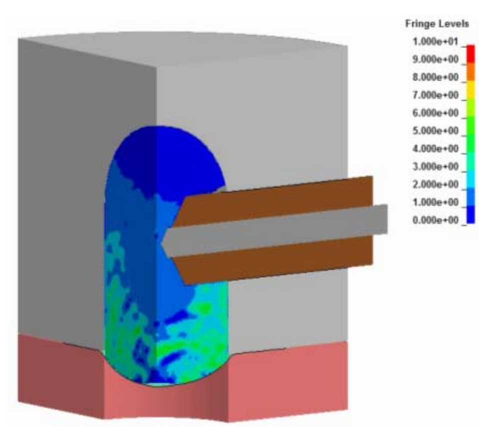


Figure 7. Distribution of the pulse pressure at the moment 245 µs

The simulated displacement and effective plastic deformation of the central point of the blank show a good agreement with the experimentally obtained values, although there is a tendency of experimental displacement being about 20…25% more than simulated value.

Conclusion

The method of simulation of electric discharge in a liquid using experimentally obtained energy input function is developed using LS-DYNA 971. The developed method is applied for simulating two specific problems: two-dimensional axisymmetric discharge in the closed cylindrical chamber and discharge in the chamber of arbitrary shape with deformable blank. The results of simulation are verified by the experimental data. The advantages of using Multi Material Arbitrary Lagrange-Eulerian approach in comparison of conventional Lagrangian approach for simulating fluids is shown. The developed technique can be used to predict process parameters and to design and optimize tools and equipment for electro-hydraulic forming.

References

[1] Aashish Rohatgi, Elizabeth V. Stephens, Ayoub Soulami, Richard W. Davies, Mark T. Smith. Experimental characterization of sheet metal deformation during electro-hydraulic forming. Journal of Materials Processing Technology, (211) 2011, pp. 1824–1833.
[2] Golovashchenko S., Mamutov V. Electrohydraulic Forming of Automotive Panels. Sixth Global Innovations Symposium: Trends in Materials and Manufacturing Technologies for Transportation Industries. Proc. of TMS. San Francisco, 2005, pp. 65–70.
[3] Bonnen, J. J.F., Golovashchenko, S. F., Dawson, S. A., Mamutov, A. V. and Gillard, A. J. (2012) Electrohydraulic Sheet Metal Forming of Aluminum Panels, in Light Metals 2012 (ed C. E. Suarez), John Wiley & Sons, Inc., Hoboken, NJ, USA. doi: 10.1002/9781118359259.ch76
[4] Hallquist J.O. LS-DYNA theoretical manual. Livermore Software Technology Corporation: Livermore, CA, 2006, 498 p.
[5] Naugolnyh K.A., Roy N.A. Electrical discharges in water, Moscow, Nauka, 1971 (in Russian.)
[6] Richtmyer R., Morton K. Difference methods for initial-value problems. Interscience Publishers a division of John Wiley & Sons, New York, London, Sydney. 1967.
[7] Vagin V.A., Zdor G.N., Mamutov V.S. Methods of research of high-speed deformation of metals, Minsk: Nauka i Technila, 1990 (in Russian.)